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Regular Paper

Effect of CNTs on Electrical Properties and Thermal Expansion of Semi-conductive Compounds for EHV Power Cables

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Abstract: Carbon black with high purity and excellent conductivity is used as a conductive filler in the semiconductive compound for EHV (Extra High Voltage) power cables of 345 kV or higher. When carbon black and CNT (carbon nanotube) are applied together as a conductive filler of a semiconductive compound, stable electrical properties of the semiconductive compound can be maintained even though the amount of conductive filler is significantly reduced. In EHV power cables, since the semi-conductive layer is close to the conductor, stable electrical characteristics are required even under high-temperature conditions caused by heat generated from the conductor. In this study, the theoretical principle that a semiconductive compound applied with carbon black and CNT can maintain excellent electrical properties even under high-temperature conditions was studied. Basically, the conductive fillers dispersed in the matrix form an electrical network. The base polymer and the matrix of the composite, expands by heat under high temperature conditions. Because of this, the electrical network connected by the conductive fillers is weakened. In particular, since the conductive filler has high thermal conductivity, the semiconductive compound causes more thermal expansion. Therefore, the effect of CNT as a conductive filler on the thermal conductivity, thermal expansion coefficient, and volume resistivity of the semiconductive compound was studied. From this result, thermal expansion and composition of the electrical network under high temperature conditions are explained.

Keywords: CNT, Carbon black, Electrical network, CTE, Conductor shield, Semiconductive, EHV, Power cable

1. INTRODUCTION

Temperature of the conductor of EHV (extra-high voltage) power cables for power transmission is about 90°C under nomal operation condition. A semiconductive compound is used as a conductor shield layer to evenly alleviate the electric field generated from stranded conductors. For this reason, the conductor shield layer must maintain stable electrical performance, especially at high temperature [2, 9-12]. Semiconductive compound and the polymer composite contain a large amount of conductive carbon black for excellent electrical properties [13]. Since carbon black is harder than the base polymer, semiconductive compounds containing a large amount of carbon black have poor extrusion processability [14].

Usually, carbon black and most inorganic additives are used in small amounts to reinforce the physical properties of polymer composite materials. A small amount of inorganic additives also restrain the thermal expansion of polymer composites [15].

On the other hand, when a large amount of conductive filler (carbon black, CNT, ...) with excellent electrical and thermal conductivity is included in the composite material, thermal

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and electrical network are formed, and as a result, the polymer composite material has thermal conductivity and electrical conductivity [16]. The semiconductive compound for power cables contains a large amount of conductive filler (carbon black), and due to the high thermal conductivity, the semiconductive layer expands more thermally under high temperature conditions [4-8]. In this paper, the correlation between thermal expansion and electrical properties was confirmed by testing the coefficient of thermal expansion (CTE) and volume resistivity according to the content conditions of the conductive filler. From this result, a recipe design of hybrid Nano-semiconductive compound that is suitable for extra-high voltage power cable was studied [1].

The results of the cited research papers and the tendency of the volume resistivity data according to the CNT content condition obtained from the experiment are compared in Fig. 1. As a result, a similar tendency was confirmed between the results of this paper (MWCNT at fixed C/B content of 16.5 phr) and the cited research papers. As shown in Figs. 1 and 2, the electrical performance of composite materials containing conductive inorganic fillers, such as carbon black and CNT, is rapidly improved under conditions where the conductive filler content exceeds the critical point [17-19]. The physical properties of the carbon black used in Fig. 2 are shown in Table 1. As the wider the specific surface area of the conductive filler is, the more advantageous network formation is, the electrical performance of the conductive composite is excellent even with a small amount. In addition, as shown in Fig. 1, electrical conductive composite materials are also affected by processing and molding conditions.

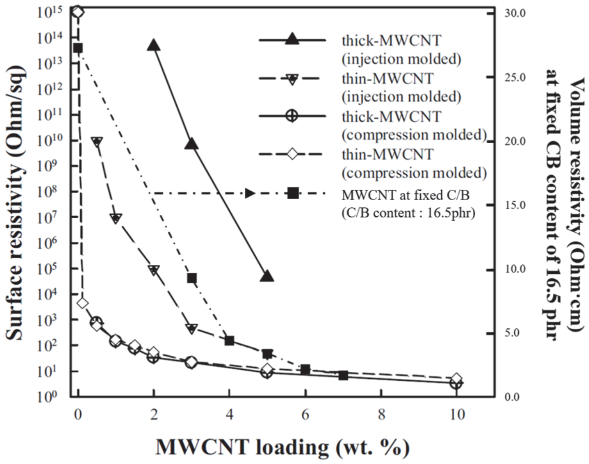

Fig. 1. Comparision the surface resistivity of PC/MWCNT and the volume resistivity of EBA/MWCNT+CB nanocomposite as a function of MWCNT weight fraction [17].

2. EXPERIMENTAL

2.1 Compounding & specimen

The recipe of the Hybrid-nano semiconductive compound designed for this study is shown in Table 3. Carbon black and CNT were used together, and the amount of carbon black was fixed and recipes with five conditions of CNT content were designed. As a reference, it was compared with a commercial product using carbon black alone. The recipes in Table 3 were tested under the conditions of Tables 4 and 5 in the Kneader compounding process of Fig. 2. The raw materials used in this

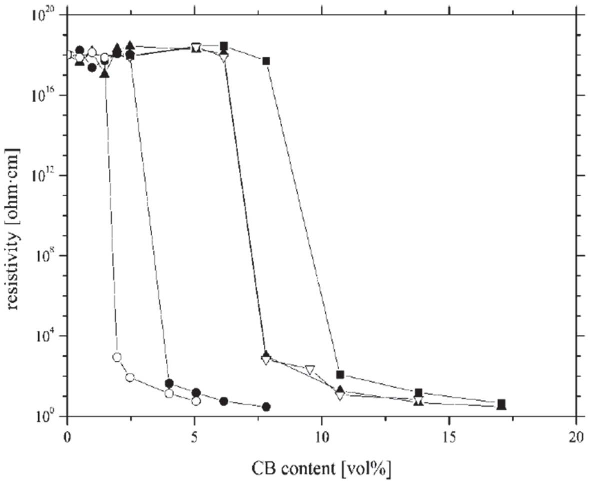

Fig. 2. Room-temperature resistivity of HDPE-CB composites as a function of the CB volume content: ■ CB1, ▲ CB2, ▽ CB3, ● CB4, ○ CB5 [18].

Table 1. Properties of the CBs used as fillers [18].

Material code	Grade	Density (g/cm³)	OAN (cm³/g)	SSA (m²/g)
CB1	Raven P-FE/B	1.92	0.98	105
CB2	Conductex 975u	1.94	1.69	226
CB3	Vulcan XC72	1.93	1.78	231
CB4	Ketjenblack EC300J	1.92	3.22	802
CB5	Ketjenblack EC600JD	1.95	4.95	1,353

study are described in Table 2.

Each sample was pre-heated at 85℃ for 60 minutes and then soaked with a crosslinking agent. Each soaked sample was molded at 200 kgf for 15 min in a hot-press preheated to 180℃ for chemical crosslinking. To test the mechanical and electrical properties, it was first molded into a flat sheet with a thickness of 1.0 mm. Then using the flat sheet, dumbbell-shape specimen for tensile strength test and rectangular-shape specimen for volume resistivity test were made.

Table 2. Description of raw materials.

Material	Remarks
EBA resin	BA content: 17%, Melt index: 7.0 g/10 min
MWCNT	Average diameter: 10 nm, Average length: 16 μm
Carbon black	Surface area: 69 m^2/g
A/O	4,4’-Thiobis (2-t-butyl-5-methylphenol)
Crosslinking	Dicumyl peroxide

Table 3. Tested recipes of hybrid nano-semiconductives.

[Unit: phr]

	Case 1 Only C/B	Case 2 CNT 3 wt%	Case 3 CNT 4 wt%	Case 4 CNT 5 wt%	Case 5 CNT 6 wt%	Case 6 CNT 7 wt%
EBA	100.0	100.0	100.0	100.0	100.0	100.0
CNT	-	3.6	4.8	6.2	7.5	9.0
Carbon black	50.0	16.5	16.5	16.5	16.5	16.5
A/O	0.5	0.5	0.5	0.5	0.5	0.5
Crosslinking	1.0	1.0	1.0	1.0	1.0	1.0
Total	151.7	121.8	123.0	124.4	125.7	127.2

Table 4. Compounding conditions in the kneader mixer.

	Mixing time	Mixing volume	Mixing speed	Chamber temp.	Compound temp.
Processing condition	17 min	85%	25 rpm	130℃	220~230℃

Table 5. Extrusion conditions of single screw extruder.

	C1	C2	DIES	Hopper	Screw speed
Setting condition	130℃	140℃	150℃	130℃	25 rpm

2.2 Conductive filler

In this study, high-purity Acetylene black grade, which is mainly used in semiconductive compounds for power cables, and CNT (carbon nanotube), which is mainly used in batteries, were used as conductive fillers.

As shown in Fig. 3, the carbon black has a spherical shape, and the CNT has a bundle type linear structure. Therefore, compared to carbon black, CNT is advantageous in forming a thermal/electrical network [20]. The mechanism by which Hybrid-nano carbon forms an electrical network is schematically shown in Fig. 4. Linear CNT is more effective in improving the electrical network than spherical carbon black by increasing a small amount as shown in Fig. 4 on the matrix.

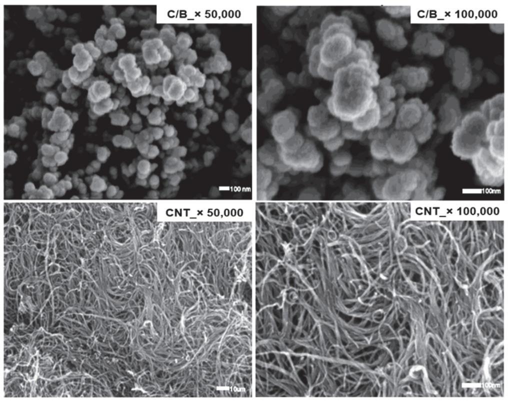

Fig. 3. Carbon black (acetylene black) & CNT (BT-1001M).

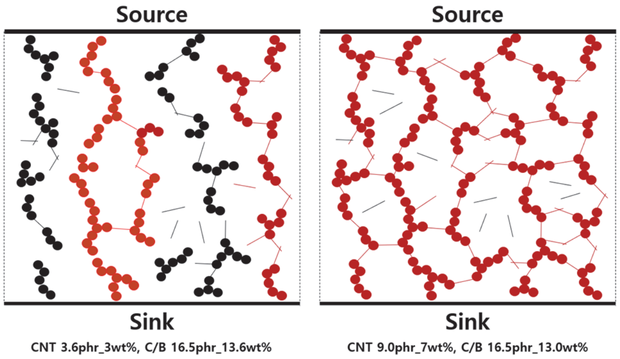

Fig. 4. Schematic of hybrid-nano semiconductives as EBA matrix.

3. TEST RESULTS

3.1 Electrical properties (at. 90℃)

The volume resistivity change was tested for 60 minutes by raising the chamber temperature of the heating oven from room temperature (at. 23°C) to high temperature (at. 90°C). As shown in Fig. 5, it was confirmed that the volume resistivity value at high temperature compared to room temperature gradually increased at the point where the content of CNT was less than 5 wt%. This is because the electrical network configuration has become weak due to insufficient CNT content. On the other hand, If the CNT content is more than 5 wt%, the volume resistivity does not increase even at high temperatures. This means that the electrical network of the conductive filler is completely formed, as shown on the right side of Fig. 4. And, it was confirmed that the volume resistivity at high temperature of the commercial semiconductive compound containing only carbon black was twice as high as that of room temperature.

3.2 Thermal properties (at. 90℃)

The thermal expansion coefficient (CTE) of the compound calculated arithmetically from the thermal expansion coefficient of each raw material and obtained by the mixing-rule was compared with the experimentally tested result. The results of Mixing rule A, which considered not only the thermal expansion coefficient of the raw materials but also their thermal conductivity (λ), had similar tendency with the results obtained experimentally. Therefore, the semiconductive compound thermally expands further due to heat transfer by the conductive filler (CNT, Carbon black) [3].

$$\begin{aligned}&\textbf{Mixing rule A} \rightarrow \sum_{n=\mathrm{EVA,CNT,C/B}} (\mathrm{Content}_n \times \mathrm{CTE}_n \times \lambda_n)\\&\textbf{Mixing rule B} \rightarrow \sum_{n=\mathrm{EVA,CNT,C/B}} (\mathrm{Content}_n \times \mathrm{CTE}_n)\end{aligned} \tag{1}$$

Figure 6 explains the experimental/theoretical CTE of the test specimens for each CNT content condition. Table 6 Thermal properties of raw materials cited were used for the calculation of the theoretical CTE by the mixing rule A and B. The thermal expansion coefficient of the semiconductive compound samples increased rapidly from the point where the CNT content was higher than 5 wt%. At this point, it is considered that the formation of a thermal/electrical network between the conductive fillers evenly dispersed in the matrix has reached a significant level. This well-connected network between the conductive fillers transfers heat well to the core of the semiconductive compound. Because of this, it expands more with heat.

Table 6. Thermal properties of raw materials [21].

	CTE (μm/m·°C)	Thermal conductivity (W/m·K)
EVA	180	0.8
CNT	20	470
Carbon black	6	200

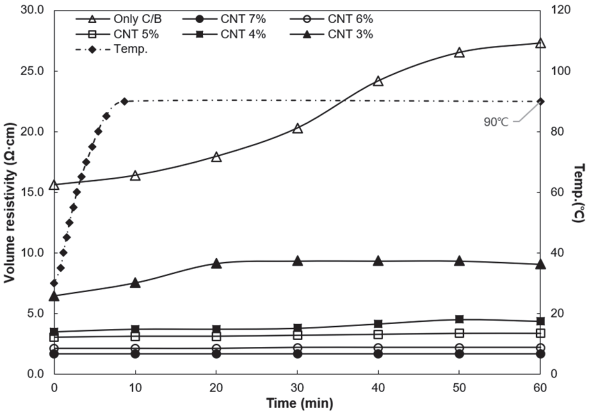

Fig. 5. Test results of volume resistivity.

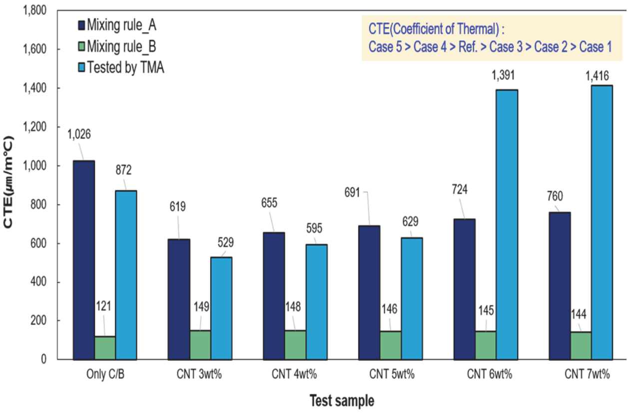

Fig. 6. Test results of coefficient of thermal expansion (CTE).

Based on these experimental results, it was confirmed that the thermal conductivity of the conductive filler directly affects the thermal expansion of the semiconductive compound containing a large amount of conductive filler.

3.3 Mechanical properties

Carbon black and CNT used as conductive fillers have excellent electrical conductivity. However, since the stiffness is very strong compared to the base polymer, it was confirmed that the tensile strength increased and the elongation decreased rapidly as the CNT content increased, as shown in Fig. 7. In the case of semiconductive compounds for power cables, elongation of 150% or more is required. Therefore, it is appropriate for the hybrid-nano semiconductive compound containing CNT and carbon black to contain less than 7 wt% CNT.

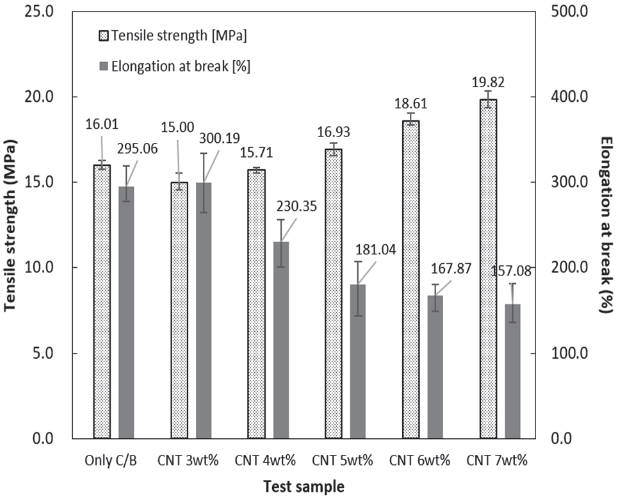

Fig. 7. Test results of tensile strength and elongation.

4. CONCLUSION

From this study, the conductive filler (33 wt%) used in the normal semiconductive compound was significantly reduced to 18 wt% based on case 4 by applying carbon black and CNT together. Although it was affected by the carbon black content condition, in this study, it was confirmed that the electrical network was maintained stably when more than 5.0 wt% of CNT was included. Due to the high thermal conductivity effect of the conductive filler, the semiconductive compound showed greater thermal expansion. Nevertheless, it is possible to stably maintain electrical performance not only at room temperature but also at high temperature by stably maintaining the electrical network of the linear CNT. The results of this study will be quite meaningful in the field of HV & EHV power cables that are always operated under high temperature conditions.

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